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Fouling release coating application as an environmentally efficient retrofit: a case study of a ferry-type ship

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Abstract
Purpose and methods The paper introduces a simple retrofit performed on a case study vessel, with the aim of assessing the retrofit's potential environmental impacts via doing a life cycle assessment. Additionally, the case presented herein strives to evidence the applicability of life cycle assessment (LCA) appraisals within shipyard representatives or managers.
Results and discussion The environmental results shown in this paper are related to cost calculations presented for the selected retrofit, underlining the potential environmental impacts from the retrofit, while appraising its economic performance.
Conclusions The paper strives to evidence that significant savings with regard to fuel costs can be achieved by the application of this retrofit to ships with a similar operational profile, but more importantly, the improved operational efficiency and the emission reductions can be noteworthy. Lastly, the results summarised intend to offer an optimistic context towards the implementation of the retrofit at a larger scale, i.e. a section of the existing fleet.

Keywords Fouling release coatings · GHG emission reduction · LCA · Maritime transportation · Shipbuilding · Ship repair · Retrofit

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1 Introduction

With the aim of staying in the forefront of a growing industry and market, while striving to be an environmentally sustainable endeavour, the International Maritime Organization (IMO)—main shipping regulatory body—has carried out and published their second Greenhouse Gas Emissions Study (Buhaug et al. 2009). The document, aside from being a comprehensive review of the kind of emissions and the quantities world shipping potentially entails, presents proactive measures to increase the environmental performance of an already existing fleet, while additionally striving to enhance future vessel designs.

In the other hand, while the life cycle assessment (LCA) methodology is currently well practised among many industries, there is still quite a lot of room for implementation with regard to the maritime transportation, shipbuilding and ship repair industries. LCA, aside from its known benefit of serving as a tool to gauge the environmental performance of a product or system, can also serve as a decision making tool (Blanco-Davis and Zhou 2014), not only to aid ship owners, but also available for shipyard representatives or managers, in order to analyse shipyard processes, improve their operations and additionally be able to offer better advice to their clientele.

The following work introduces a relatively simple retrofit performed on a case study vessel, with the aim of assessing the retrofit's potential environmental impacts via the application of the LCA methodology. Additionally, the case presented herein strives to evidence the application of LCAs within shipyard users (Blanco-Davis 2013a), similarly as a tool to improve design before a shipbuilding or repair operation takes place (Koch et al. 2013), as well as an instrument for eco improvement of the shipyard processes. Lastly, the results from environmental impact analyses shown in this work are *tied up* to cost calculations performed for the selected retrofit; the logic behind this is that aside from underlining the

potential environmental impacts from the retrofit, its economic performance can also be appraised.

The reader should know that the case study included herein is but one of four different case vessels, chosen as a sample part of a larger assessment, which was carried out while participating on a 3-year long collaborative R&D project named "Eco innovative refitting technologies and processes for shipbuilding industry promoted by European Repair Shipyards", in short Eco-REFITEC; this project was funded by the European Union's RTD Seventh Framework Programme (del Castillo and Blanco-Davis 2012).

2 Case study general aspects

2.1 Introduction

The current high prices on fuel, specifically heavy fuel oil (HFO)—popular diesel fuel choice among commercial vessels—have propelled the need for ship owners and managers to search for practical ways to get the most out of it. While there are various ways to do just that, arguably the *must-have* addition to any type of commercial vessel is the application of an efficient antifouling paint system on the ship's underwater hull. These types of coatings, aside from offering a level of corrosion protection, strive to prevent bio fouling or the attachment of e.g. algae, barnacles and etcetera to the ship's hull and consequently increasing the drag while additionally incrementing the ship's fuel consumption.

While not ideally, most fleet managers will focus on an antifouling paint system due to the high cost of HFO, rather than the potential emission savings that the system may sustain. As a testimony of the above mentioned, the price for HFO on January 2013 had reached a level of around US$630/t (380 centistokes HFO), and as a comparison, the price dating back to January 2000 was close to US$200/t (Bunkerworld 2013). Additionally, since the IMO banned the use of tributyltin-based coatings containing toxic compounds that acted as aggressive biocides (Champ 2003), other options must be considered as tributyltin substitutes with distinct antifouling performances (Okamura and Mieno 2006).

The proposed solution emphasises the application of a silicone-based fouling release coating (FRC) for the underwater hull surface, as a retrofit. The benefits that this type of paint may offer are underlined by the improvement of speed and the reduction of the fuel and lube oil consumption; this last in turn may offer considerable environmental benefits (i.e. less consumption of hydrocarbons and less unfavourable emissions emitted).

2.2 Vessel description

The case vessel is a *Ro-Ro passenger ship*—the abbreviation stands for roll-on/roll-off vessel. This type of ship is designed to carry wheeled cargo (e.g. automobiles, trucks, trailers and railroad cars), which, by the use of their own wheels, is "rolled-on" and "rolled-off" the ship while in port. This particular vessel is a combination of the above and also a cruise ferry; the last means that the vessel, additionally from transporting vehicles, transports passengers. Many passengers travel with the ship for the cruise experience. See Table 1 for the vessel's particulars.

The reader should know that while this vessel is a real case ship, due to confidentiality arrangements, the name of the vessel and owner has been kept undisclosed. One of our shipyard partners within the Eco-REFITEC project, Astilleros de Santander SA (ASTANDER), aside from serving as a liaison between the vessel's owner and the project, has also performed the specified retrofit. A significant quantity of the data collected for the assessment has been facilitated by ASTANDER. The reader should refer to Blanco-Davis (2013b) for more information with regard to the above.

2.3 Operational principles and implementation of the proposed retrofit

The application of the proposed silicone paint entails specific steps to be followed; these are commonly underlined by the paint manufacturer, depending on the exact type of paint and location where it will be applied (i.e. the location of the yard and the physical climate properties of the place). The FRC system is based on a novel silicone elastomer technology, which prevents fouling by its physical characteristics. The smooth surface provided by the system minimises adhesion of fouling organisms to the hull, by the hydrodynamic forces produced when the vessel is in motion (Mirabedini et al. 2006).

Nevertheless, since the system is silicone-based, the risk of silicone contamination to the surroundings, e.g. other parts of the vessel using a different paint system and adjacent machinery, must be kept in check. To avoid contamination of silicone onto other surfaces, it is advised that the underwater hull area be covered before the application of the paint (see Fig. 1). It is also recommended to use dedicated application equipment.

For optimal coating adhesion, the use of hydroblasting instead of conventional grit blasting is suggested. Hydroblasting consists in using high pressure (600 to 800 bars) water flows to remove the existing antifouling paint system, while cleaning the hull surface of salts and other contaminants. This operation requires special machinery, which comprises high pressure pumps and special nozzles. The use of hydroblasting instead of grit blasting reduces the air pollution produced by the latter, while additionally dismisses grit

Table 1 Vessel particulars

Type of vessel:	Ro-Ro passenger ship	Deadweight (DWT):	6,515 t
Year of built:	2001	Gross tonnage (GT):	32,728 t
Length overall (LOA):	203.9 m	Net tonnage (NT):	13,081 t
Length between perpendiculars (LBP):	185.6 m	Decks:	Nine, including one hoistable deck
Breadth:	25 m	Hull materials:	Naval A grade steel
Depth:	9.1 m	Hull connections:	Welded
Displacement:	20,150 t	Power (main engines):	48,000 kW at 510 rpm (four diesel engines)

cleaning tasks related to post-blasting—which in turn may permit cost savings–.

In the other hand, this type of application entails additional equipment in comparison to the grit blasting operation. After the paint application, conditions of temperature, dew point and humidity, must be closely monitored. Therefore, aside from canvasing the entire underwater hull area, it is often required to maintain the above-mentioned conditions by the use of dehumidifiers and heaters, to allow proper curing of the paint. These types of equipment may incur in relevant energy consumption, and it would be interesting to see how they fare against the environmental benefits procured by the use of the hydroblasting. Both operations are included in the following assessment.

3 LCA modelling

The following study has been carried out following the requirements, guidelines and suggestions of the ISO 14040 and 14044 International Standards for the implementation of LCAs (ISO 2006a, b). Additionally, the model discussed herein is based on an LCA predecessor; some of the formulation included in Johnsen and Fet (1998) has been thoroughly

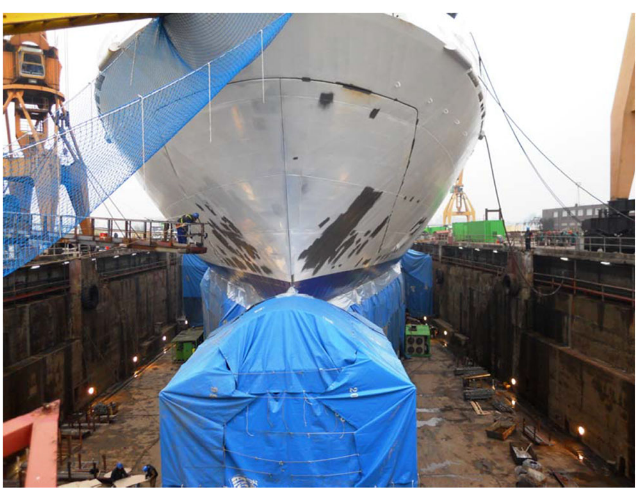

Fig. 1 Canvassed underwater hull area for proper paint application

used as a starting point for the model and updated and expanded where possible and necessary.

Lastly, because of the close similarities of the vessel described in Johnsen and Fet (1998), also some of the data in the predecessor model—while properly scaled to the chosen case study—has been utilised to complement data that due to time constraints was not readily available for the purpose of the following study. In its majority, this data comprises information about processes from the vessel's building or manufacturing phase, as well as its end-of-life or scrapping phase; these data is not considered to influence results of the retrofit considerably, given that the main differences will occur during the operational and maintenance phases, as described later. Consequently, the vessel's life cycle phases included in the assessment are as follows: manufacturing, operation, maintenance and end-of-life.

3.1 Goal and scope of the study

The goal of the study is to evidence the benefits of the switch from conventional antifouling coating to the FRC scheme, with the testimony of the environmental life cycle evaluation applied to the vessel in question. The environmental evaluation is done taking into account the previous performance of the conventional coating system versus the most recent FRC scheme application, via a scenario comparative assertion. The results are further supported through fuel consumption performance. Lastly, a cost–benefit analysis is performed, taking into consideration the additional expenses that the FRC scheme incurs, with regard to the potential fuel cost savings; this will underline the feasibility of this alternative option.

The scope of the study comprises the Ro-Ro passenger ship herein described. The vessel is broken down into sub-systems; sub-systems are then broken down into system elements and system elements consequently broken down into processes (Johnsen and Fet 1998). With regard to the proposed case vessel as a whole, some systems have been included in the assessment, while others have been disregarded. The reason behind this logic, aside from the inherited necessity of simplifying some data due to the holistic nature of the LCA, is also to take into consideration the most relevant systems, while ignoring the ones that are considered trivial (please refer to

Johnsen and Fet (1998) and Blanco-Davis (2013b) for more information with regard to the choosing of the systems). The sub-systems considered are graphically summarised in Fig. 2. Lastly, the function of the ship is considered to be the transportation of passengers, cars and trailers.

3.1.1 Ship's operational profile

The vessel's current operational frequency entails the completion of three trips per week from the south of England to the north of Spain and back. The average distance per trip, considering the two different end locations, is 560 nautical miles, undertaken at an average speed of 25 knots. The last would mean that the average sailing time is 22.4 h per trip.

While the ship does have somewhat of a regular sailing schedule, it varies slightly during the year. It undergoes scaled-down maintenance yearly for an assumed period of 2 weeks per year, which leaves 50 weeks a year for operation. Taking into consideration the amount of trips undertaken per week, the ship sails 150 trips per year. This last would account for 3,360 h of sailing per year, with a resulting 5,400 h per year spent at port. The relevance behind this is that the ship's engines are constantly running during sailing, while at port, little fuel consumption takes place (the ship is normally connected to shore for electric power and only uses its small generators for emergency standby).

As a practical assumption, every 2.5 years, the ship will undergo heavy maintenance including dry docking. With an assumed lifetime of 25 years, this would mean that the ship would undergo heavy maintenance ten times during its lifetime (including initial shipyard call during construction). Lastly, the ship is assumed to sail for Asia to be scrapped after 25 years of service.

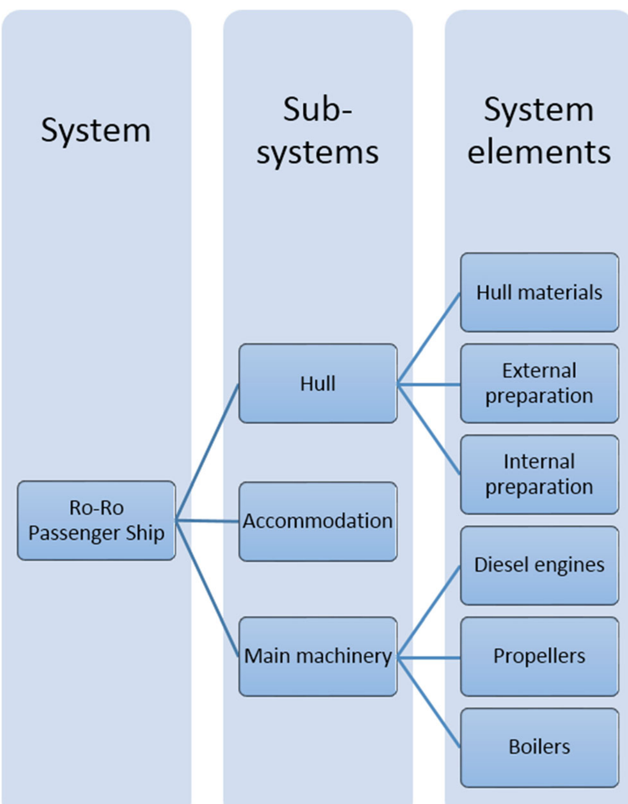

Fig. 2 Graphical representation of the system to be assessed, as adapted from Johnsen and Fet (1998)

3.1.2 Boundary setting and data quality requirements

The baseline LCA model includes the life cycle phases previously mentioned and aims to account for material and energy exchanges from raw material extraction through recycling or disposal. However, the scenarios defined in the following sections will only comprise changes within the operational and maintenance phases, as the application of the retrofit is performed during this defined interval (i.e. the results from painting scheme retrofit will only be present during the operational and maintenance phases; the other phases remain unchanged).

With regard to processes' definitions, the study refers to data mostly from Europe (EU-27); this includes cradle-to-gate analyses for many of the processes found within the construction, operation and maintenance phases. It should be noted that a medium emphasis has been put on data quality; the main reason behind this resolution, as previously mentioned, is the constraint of time for this particular assessment.

Worth of mention is that aside from some of the used data acquired from Johnsen and Fet (1998) and ASTANDER, there are various inputs taken from the GaBi Professional Database (PE-International 2013). Similarly, a small part of the data comes from certain estimations and calculations needed, where no data was publicly available. Lastly, the scrapping phase is highly simplified due to lack of data, and a relevant absence of cradle-to-gate data for processes is acknowledged.

3.2 Life cycle inventory analysis

As far as this phase of the assessment goes, relevant inputs relate data to unit processes and to the system's predefined functional unit; the reader should refer to Blanco-Davis (2013b) for more information. System key components are then defined, including their inputs needed in order for modelling procedures. Electrical consumption, for example, is calculated for each energised component under a per hour rating and then extrapolated to their life cycle consumption, taking into consideration the vessel's assumed lifetime of 25 years.

3.2.1 Flow chart development

A sample plan is below discussed, as a way to offer a summarised description of the modelling phase while using GaBi Software (GaBi 2013). Similarly, some of the system's key elements are briefly mentioned, in order to allow the reader to understand the baseline formulation behind the modelling.

The hull construction plan, for example (see Fig. 3), includes various processes tied-up together and driven by a main user-defined input: hull weight. When the hull weight is defined by a user, flow quantities will change automatically—always keeping an assigned ratio—in order to accommodate for the quantity of material being requested. Therefore, if the user increases the input material so will increase the welding seams, as well as the consumption of grit for example, or similarly electric energy; following this reasoning so will increase the emissions caused. The reader should be aware that this last example does not relate directly to the retrofit in question, but to a sample operation(s) which could take place during the construction phase of the model.

With regard to the flow diagram in Fig. 3, the steel is assumed to be transported by ship to the shipyard, and the actual distance can be inserted by the user into the

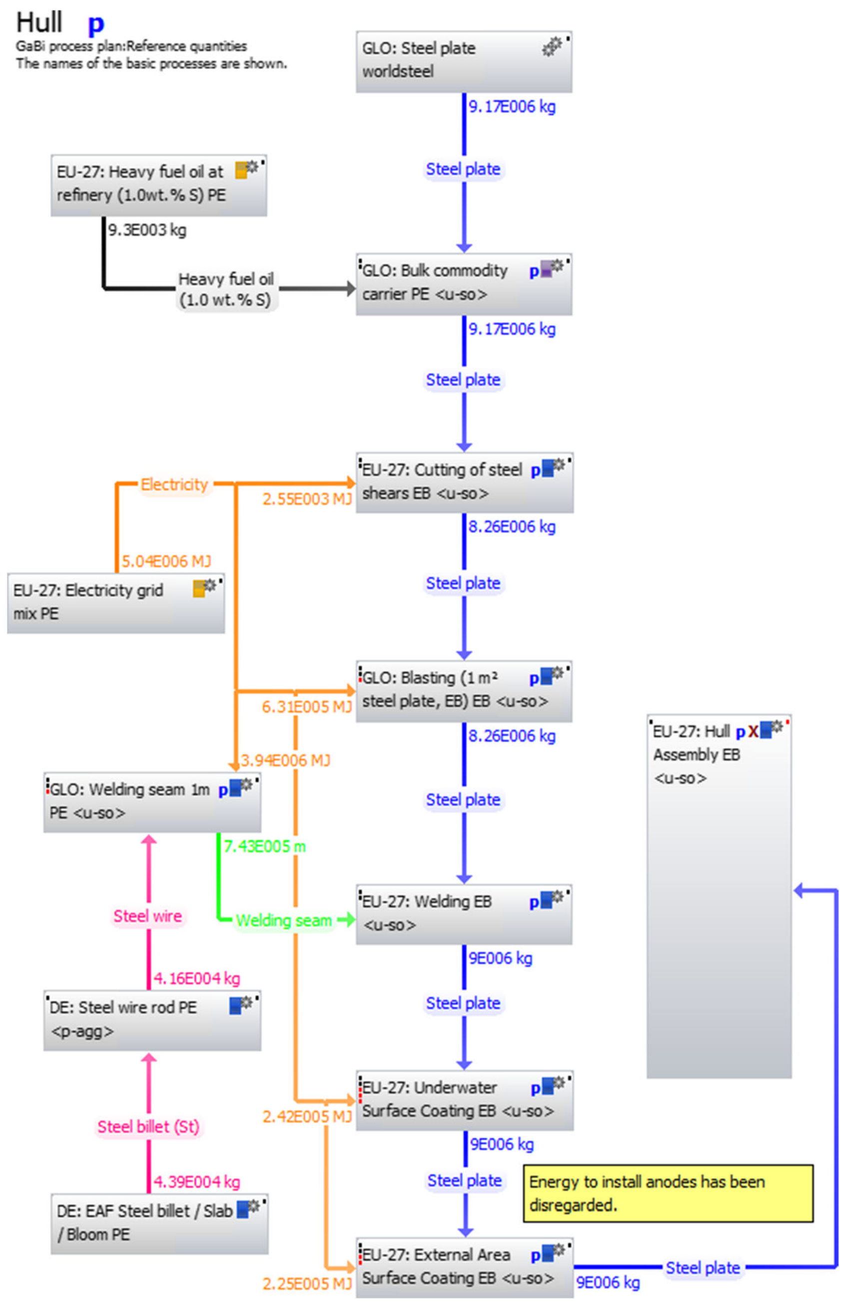

Fig. 3 Flow chart from the hull construction plan, as developed in GaBi (2013)

aforementioned model (an assumed distance of 1,000 km is chosen for the model presented herein). This will comprise the emissions produced by the cargo ship transporting the materials necessary to fulfil the user requirement. Additional user inputs include grit consumption factor, external as well as internal hull areas to be grit blasted and painted, and paint consumption factor. A list of 70+ user-defined parameters is available for this particular model (Blanco-Davis 2013b).

While the end-of-life phase does not influence retrofit results, it is however included in the baseline model. As far as hull materials go, the end-of-life scenario assumes that most of the ship is made out of steel, and a user input defines how much percent of this steel ends up as steel scrap for recovery, or other waste. Currently, it is set up for 80 and 20 %, respectively. Additionally, taking into consideration the ship travels to a scrapping yard, a transportation process with consumption and emission factors similar to that of a mid-size vessel simulates the emissions incurred with the user-defined input of distance (for this particular case, an assumed distance of 10,000 km is used). Unfortunately, the end-of-life scenario is where most data is lacking, and this phase is an ideal candidate for future model refinement.

Coating processes, relevant within the retrofit assessment, take place during the construction and maintenance phases. The most important user input to allow these processes to be simulated is the area of application, e.g. the underwater hull area, which in the case for the Ro-Ro passenger vessel amounts to 5,600 m^2. Similarly as the hull example explained above, material and energy inputs will change accordingly, including paint consumption and generated waste, for example. Base (or primer) and end coats are assumed solvent-based paints and following that logic, emission distribution profiles such as the one presented in Table 2 are included as emission factors tied to the coating application.

With regard to the maintenance phase, the addition of three coating processes is relevant: HP water wash (250 bar), HP water blast (800 bar) and dehumidifier/heater. The processes are defined through consumption data supplied by ASTA NDER. The last process is available only if the user decides to use it, i.e. if the paint scheme requires the use of dehumidifiers. It is relevant to point out that the end user can also choose whether to use grit blast or water blast, or a combination of the two, which, along the lifetime of a vessel, could very well happen. The advantage of this option is that the user could compare the environmental score of the baseline scenario (e.g. grit blast throughout the ship's 25 years of life) versus the alternative of water blast throughout the same period or a fraction of this time.

Lastly, diesel engines, propellers and boilers are simulated similarly as in Johnsen and Fet (1998) and highly simplified with regard to cradle-to-gate data. The following emission factors for the diesel engines are included during the operational phase, which indeed are a mixture of the actual engines' performance and data from the predecessor model (see Table 3). The reader should note that the type of fuel considered is heavy fuel oil (HFO), with a sulphur content assumed equal to 1 % of the fuel weight. Engine performance is also assumed constant during operation.

3.2.2 Inventory results

The life cycle inventory has produced various interesting results, where aside from different resources consumed and emissions emitted, a summary of significant emissions to air produced along the lifetime of the ship is relevant (see Table 4). While a pertinent table, not a surprising one, since it is known that most emissions are produced during the lifetime of a vessel, occur during the operational phase of its lifetime. However, the contribution by this phase is not only sizeable, but it exceeds the emissions produced by other phases at significant differences.

The reader should be aware that these results belong to the Ro-Ro passenger vessel, while under the assumption that this vessel changes its coating scheme from conventional antifouling to FRC, at the middle of its lifetime. Therefore, it has been assumed that the first five times that the ship undergoes dry dock maintenance, it does so under the conventional antifouling treatment (i.e. grit blasting

Table 2 Volatile organic compound (VOC) specification profile for solvent-based paints

CAS no.	NPI-listed substance	Weight % (total=100 %)
110-82-7	Cyclohexane	0.52
141-78-6	Ethyl acetate	2.04
67-64-1	Acetone	1.27
78-93-3	Methyl ethyl ketone	0.54
108-10-1	Methyl isobutyl ketone	0.36
1330-20-7	Isomers of xylene	8.17
108-88-3	Toluene	37.87
100-41-4	Ethyl benzene	0.54
	All other VOCs	48.69

According to NPI (1999)

Table 3 Consumption and emission factors for diesel engines

Diesel (HFO 1.0 wt% S)	Material consumption	200.00 g/kWh
NO_x	Inorganic emissions to air	16.70 g/kWh
CO	Inorganic emissions to air	0.36 g/kWh
Hydrocarbons	Emissions to air	0.20 g/kWh
CO_2	Inorganic emissions to air	670.00 g/kWh
SO_2	Inorganic emissions to air	4.20 g/kWh
Oil sludge	Hazardous waste	1.20 g/kWh

As adapted from Johnsen and Fet (1998)

Table 4 Mass balance–life cycle of Ro-Ro passenger vessel

Relevant emissions to air during all life phases and aggregated totals, absolute values (kg)

Flows	TOTAL	Ship construction	Ship maintenance	Ship operation	Ship scrapping
Carbon dioxide	1.67E+09	2.64E+07	3.84E+06	1.64E+09	4.26E+04
Carbon monoxide	1.42E+06	3.56E+05	4.14E+04	1.02E+06	1.15E+02
Nitrogen oxides	3.76E+07	4.21E+04	6.15E+03	3.75E+07	1.03E+03
Sulphur dioxide	1.03E+07	5.17E+04	8.44E+03	1.02E+07	6.81E+02
Hydrocarbons (unspecified)	4.22E+05	2.90E+01	7.39E+00	4.22E+05	6.44E-03

and conventional antifouling coating application), while changing and continuing with the FRC scheme from its lifetime midpoint and onwards.

The above and the following will be further reviewed in the next sections; however, the reader should know that according to data recently provided to ASTANDER by the ship's owner, the successful FRC application has allowed the ship to use only 3 out of their 4 engines, while maintaining the same speed and schedule produced previously by all four engines under the conventional antifouling scheme. The figures presented in Table 4 are under the assumption that during the first half of the life of the ship, all four engines were used at about 62 % load, while during the latter half, three engines were used at about 70 % load.

3.3 Life cycle impact assessment

The impact category presented herein is defined as the global warming potential by CML, in a hundred years' time frame. The classification and characterisation of emissions will be according to CML 2001, with a characterisation factor from November 2010 (CML 2010). This characterisation will determine how much emissions produced by the assessed Ro-Ro passenger vessel, including its different scenarios, contribute to global warming potential, related to kilogram of CO_2 equivalents.

As briefly mentioned, two scenarios are taken into account to gauge the impact of the performed retrofit. The first scenario is defined by two major assumptions: the Ro-Ro passenger vessel undergoes conventional antifouling treatment

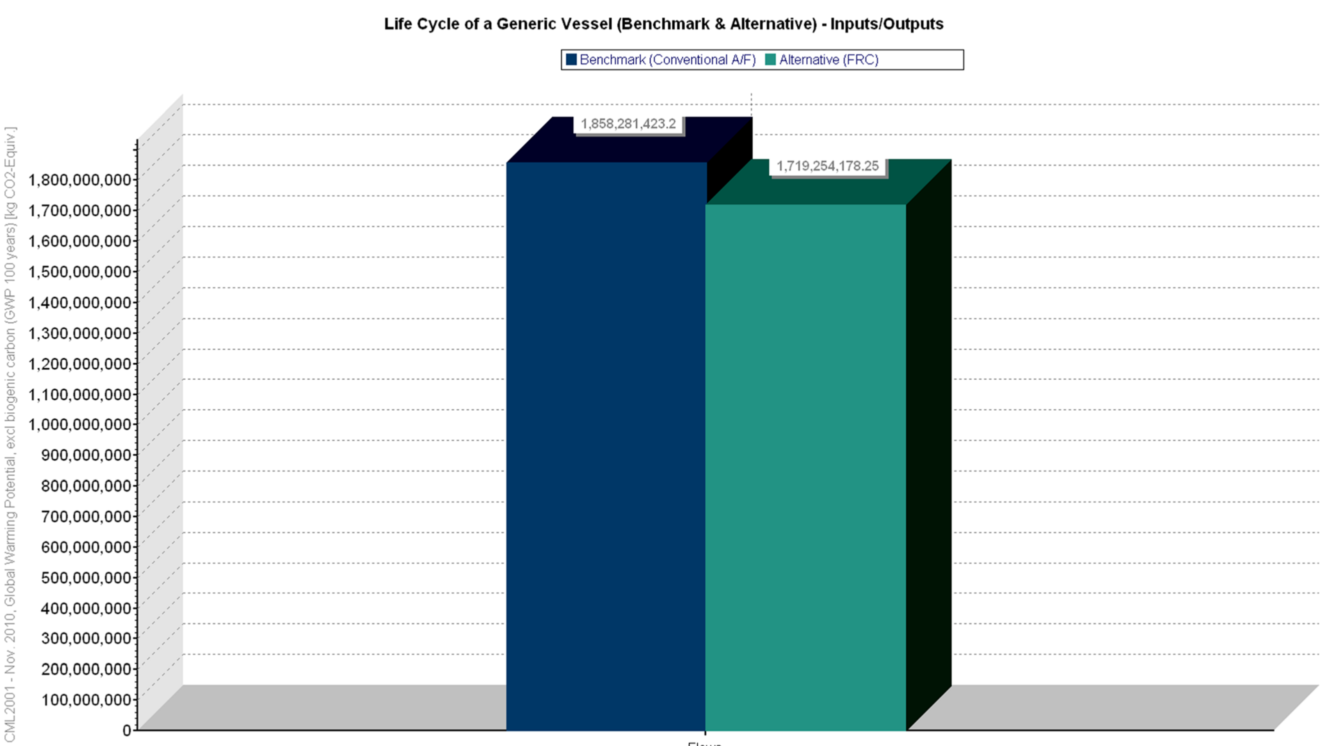

Fig. 4 Scenario comparison between conventional antifouling (benchmark) and FRC (alternative) application, CML 2001, Nov. 2010, Global Warming Potential (GWP 100 years)

ten times during its lifetime of 25 years (i.e. it undergoes grit blasting and conventional antifouling application), and additionally, it utilises 4 out of its 4 main engines while at sea at an average 62 % load.

The second scenario assumes that the vessel in question changes to FRC at the midpoint of its lifetime, meaning that the first five times that the ship undergoes coating maintenance, it does so under the conventional antifouling treatment. Additionally, under the novel FRC scheme, which reduces drag, the ship is able to now use 3 out of its 4 engines, at an average of 70 % load (it is a fact confirmed by the owner that the engines are being rotated per voyage since the FRC application, using 3 out of 4).

The first scenario, including the conventional antifouling system is considered the "benchmark scenario", while the second one, which includes the application of the FRC during the midpoint of the life of the ship, is considered the "alternative scenario".

The main differences between the results of the two scenarios are produced mainly by the following:

- The use of three engines instead of four for the remaining 12.5 years of lifetime of the ship (alternative scenario).
- Fifty-percent less grit blast application, meaning less resource usage and reduced electric consumption (alternative scenario).
- High-pressure water blast (800 bars) takes the place of the grit blast operations (alternative scenario); however, it is assumed that it is only performed twice during the remaining 12.5 years (once as an initial application, the second one as a maintenance operation). The reason behind this assumption is that the FRC requires reduced maintenance, mostly incurring in easily removing the attached slime, if any, and minimal "touch-up" coating application. Nevertheless, it is assumed that full underwater hull maintenance takes place at some point before the initial application and the end-of-life.
- The FRC application is supported by the use of dehumidifiers (alternative scenario), which incur in electric consumption. Because both the HP water blast and the use of dehumidifiers occur twice under the remaining 12.5 years, it is not complex to see the positive difference versus the grit blast operation occurring five times during the preceding 12.5 years of the vessel's lifetime.

The results found in this section of the assessment evidence the environmental improvement resulting from the application of the FRC scheme on the case vessel (alternative scenario). A significant difference of 1.39E+08 kg of CO_2 equiv (139,027 t of CO_2 equivalents), which means a 7.53 % drop, is brought about while taking into consideration the main differences previously mentioned for the two scenarios (see Fig. 4). Furthermore, it would be interesting to narrow down when does this drop in emissions takes place, acknowledging beforehand that the main differences will take place during the operational and maintenance phases. The above total is distributed within the four different life phases of the vessel's life cycle (see Table 5).

Under the maintenance phase, a drop is shown in the alternative scenario of 3.61 % in global warming potential (GWP) emissions versus the benchmark scenario (totalling 170 t of CO_2 equivalents). Similarly, the *ship operation* phase shows a drop of 7.65 % in the alternative scenario, compared to the benchmark scenario, and totalling a relevant 1.39E+08 kg CO_2 equiv (138,857 t of CO_2 equivalents); the last means that this phase is the most influential with regard to the overall emissions drop, along the lifetime of the vessel. This is not surprising if one is to take into consideration the reduction in emissions that would incur using three engines instead of four, while additionally incurring in fuel savings.

3.4 Further results and identification of significant issues

3.4.1 Cost calculations

The data gathered for the FRC application can be used for a cost–benefit analysis, with regard to the initial expenditure and the service costs throughout the rest of the life of the vessel versus the calculated fuel cost and emission savings.

It is difficult to isolate dry docking costs for one particular maintenance operation, since more often than not, a lot of combined repair tasks are taking place while in dry dock; in this case, it is assumed that only paint-related tasks are taken into consideration for the benefit of the cost calculation. The FRC capital expenses (CaPex) therefore comprise various shipyard tasks such as the removal of sea chests grids, high pressure water wash, high pressure hydroblast, hull canvas protection, primer application, FRC application, dehumidifiers and others; in summary, it totals 274,894.28 €.

Similar tasks are listed under the maintenance or operational expenses (OpEx) for the FRC retrofit, with the difference that some tasks have to be performed every time the ship goes to dry dock (e.g. removal and cleaning of sea chest grids and high pressure hull water wash), while others do not (e.g. high pressure hydroblast and hull canvas protection). The cost of operational expenses for any given year, assuming that the FRC application took place midway through the life of the vessel (at 12.5 life years) and that the next dry dock would take place 2.5 years afterwards (at 15.0 life years), with a remaining 10 years of operation within the assumed lifetime (25 years life), is calculated at 41,464.64 €.

The objective of the following cost–benefit analysis is to evaluate the cost-effectiveness of implementing the FRC scheme alternative over time and assessed by way of its environmental performance and fuel savings. By using a previous estimate regarding the initial cost of implementing

Table 5 Life cycle of Ro-Ro passenger vessel—scenario comparison between conventional antifouling and FRC application

Benchmark (conventional A/F) (kg CO_2equiv.)				Alternative (FRC) (kg CO_2 equiv.)			
Ship construction	Ship maintenance	Ship operation	Ship scrapping	Ship construction	Ship maintenance	Ship operation	Ship scrapping
2.89E+07	4.71E+06	1.83E+09	4.40E+04	2.89E+07	4.54E+06	1.69E+09	4.40E+04

CML 2001, Nov. 2010, Global Warming Potential (GWP 100 years)

the FRC scheme and a yearly figure for its maintenance cost, including a discount rate, and lastly using the estimate of the rest of the life of the vessel after the application to be that of 12.5 years, the present value (PV) of the FRC scheme is calculated (see Table 6) using the following formulation:

$$\mathrm{PV} = \mathrm{PV}_0 + \mathrm{FV}(1-(1+i)^{-n})/i \tag{1}$$

Present value, as utilised similarly in HSE (2002), where

PV_0 Amount spent initially for the implementation (capital expenses) of the BWTS.
FV Cost of operative expenses, for any given year.
i Interest rate, where a uniform rate of 5 % has been used for the purposes of this study.
n Lifetime of vessel (years).

As mentioned beforehand, the case vessel was previously using four engines out of the four fitted onboard, prior to the FRC application. Taking into consideration that the case vessel was previously consuming 128 t of fuel per trip and after the application of the FRC, an improved consumption of 109 t of fuel per trip has been reported (both figures while on an economical cruising mode, as informed by the owner) and additionally inferring the shutdown of 1 engine out of the 4 onboard per trip, the following can be deduced, under the previous premise that the vessel performs 150 trips per year and that the fuel savings stay constant throughout the rest of the life of the ship:

128 t/trip−109 t/trip=19 t of HFO saved per trip
19 t/trip×150 trips/year=2,850 t of fuel saved per year
2,850 t/year×12.5 years=35,625 t of fuel saved after the retrofit.

The next practical thing to do would be to use the future cost of fuel and convert it to PVs, in order to compare the savings figure caused in turn by the PV (or the investment) of the performed retrofit. However, fuel prices may observe an extreme fluctuation in a relative short period of time. While it is almost certain that bunker fuel prices will not be exceptionally below the present costs, predicting future fuel costs is very difficult. Having underlined this fact, the figure of US$630/t (380 cSt) as the price for HFO on January 2013 is used (Bunkerworld 2013) and assumed to remain constant throughout any given year, with a linear discount rate of 5 % through 12.5 years; with the last emphasised, the following can be deduced:

2,850 t/year×US$630/t=US$1,795,500.00/year (1,311,712.50 €/year) in fuel cost savings for any given year.

Using the previously expressed PV formulation, with a slight modification to arrange for the conversion of the future fuel saving values, the following PV savings are calculated:

$$\mathrm{PV} = \mathrm{FV}(1-(1+i)^{-n})/i \tag{2}$$

Similarly as before, where

FV Cost of fuel savings, for any given year.
I Discount rate, where a uniform rate of 5 % has been used for the purposes of this study.
n Lifetime of vessel (years).

The above formulation results in the PV of total fuel saved (after 12.5 years) of 11,978,094.81 €. Aside from this significant potential cost savings, the above figure means that the initial payback period of the investment (the implementation of the FRC scheme halfway through the life of the vessel) is well within the first year after the implementation. In fact, assuming that fuel prices stay constant throughout the first year, the following can be inferred:

19 t of HFO saved per trip×US$630/t=US$11,970.00 (8,744.75 €)
653,534.75 € (PV cost of implementing the retrofit) ÷ 8,744.75 €=74.7 trips, meaning that after 75 trips, half year of operation, the retrofit investment is paid back by the fuel savings procured.

Furthermore, while there has been mention of the IMO developing a preliminary maritime emission trading scheme (METS) as a potential greenhouse gas (GHG) reduction policy in Buhaug et al. (2009), it is not yet integrated into its well-

Table 6 Present value results for the FRC retrofit

CapEx	274,894.28 €
OpEx	41,464.64 €
Present value cost of the retrofit	653,534.75 €

established predecessor, the EU Emissions Trading Scheme (EC 2013). This METS, nevertheless, would allow trading not only between ships, but also significantly enough between other sectors. Assuming, for example, an average 22 € per ton of CO_2 (CCC 2009), the environmental performance procured by the retrofit herein assessed would have the following economical equivalent, adding an additional positive context to the coating system implementation:

$$139{,}027 \text{ t of } CO_2 \text{ equivalents} \times 22 \text{ €/t } CO_2 = 3{,}060{,}706.00 \text{ €}.$$

The following table, which summarises the end results of the cost–benefit analysis, further underlines positive arguments towards the implementation of the retrofit assessed within the Ro-Ro passenger vessel case study (see Table 7).

3.4.2 Retrofitting the existing fleet

The assessment presented herein has propelled interesting results, which in turn are worth further valuations with regard to the retrofit implementation at a greater scale, for example, applied to a section of the fleet. While it is understood that the obtained results are directly related to the ship's type and its operational profile, a collation of properly filtered data could give us an idea as to the magnitude of the application of the FRC scheme at a larger scale.

Using Lloyd's Register Fairplay World Shipping Directory data (Lloyd's 2014), while accounting globally for all Ro-Ro passenger vessels with ±2 years within the built year of the case vessel presented herein and further filtering totals by only including vessels with 15,000 gross tonnes or more and 15,000 kW of power or more, the average figures found in Table 8 are obtained. These filters have been applied because they circle down on vessels with similar characteristics as the case vessel (see Table 1), specifically, the year of construction, which could then mean that similar results could be achieved by performing the retrofit midway through their lifetimes.

Worth of mention is that the figures presented in Table 8 include our case vessel but additionally ignore if any of these ships have undertaken any change of antifouling scheme. Assuming that they have not undertaken any different treatment with regard to conventional antifouling, 71 ships in total could potentially benefit from relevant fuel cost savings and, more importantly, significant emission reduction figures, as similarly presented in this study.

It would be bold to numerically extrapolate any type of conclusion as to the savings and emission reductions involved by using only the above preliminary averages; however, they aim to offer the reader an optimistic context. Lastly, it is important to note that this type of retrofit may also be applied to other types of ships, different from ferries, and that the positive results previously addressed could be proportional.

Table 7 Cost–benefit analysis versus calculated fuel costs and emission savings

Present value cost of the retrofit	653,534.75 €
Total fuel savings after the performed retrofit (after 12.5 years)	35,625 t of HFO
Potential present value of total fuel saved (after 12.5 years)	11,978,094.81 €
Savings of CO_2 tonnes under the CML 2001, Nov. 2010, GWP (100 years)	139,027 t of CO_2 equivalents
EU Emissions Trading System €/tonne of CO_2 equivalent	3,060,706.00 €

4 Conclusions, limitations and future recommendations

With regard to the Ro-Ro passenger vessel case study, the successful application of the LCA methodology has served to evidence the benefits incurred by the implementation of the FRC scheme over the conventional antifouling coating. Furthermore, cost–benefit analysis calculations have offered an additional context in which this type of retrofit is not only supported but could be favoured among similar ship types.

Worthy of note is that this particular vessel is a multifunctional ship type, as it is meant to be used not only as a transportation mean, but additionally as a pleasure/hotel craft. This presents an issue, which underlines the incomparability of the environmental score from this ship, versus another means of similar transportation, e.g. a containership. Therefore, it is of relevance to acknowledge that the LCA model presented herein assesses environmental scores comparable mostly to that of a similar type of ship, with the same functionality.

With regard to vessels with similar functionalities, it would be interesting to further gauge and *encourage* the application of the proposed retrofit at a greater scale, for example, applied

Table 8 World fleet analysis report for Ro-Ro passenger vessels filtered by year, gross tonnage and total kW

Year of built	# of Ships	Average length in metres (LBP)	Average main engine (total kW)	Average DWT	Average GT
1999	7	170.17	25,180	5,929	30,547
2000	10	167.96	37,456	6,087	27,004
2001	26	179.74	41,252	6,607	34,266
2002	17	178.91	37,973	6,326	30,747
2003	12	177.38	34,375	7,284	34,062
Totals	72	174.83	35,247	6,447	31,325

As adapted from Lloyd's Register, Fairplay World Shipping Directory (Lloyd's 2014)

to a section of the fleet, as mentioned previously. Significant savings with regard to fuel can be achieved by the application of this retrofit to ships with a similar operational profile; but more importantly, the improved operational efficiency and the emission reductions can be significant as has been supported herein by arguments, data and the results provided.

Additionally, the following is aimed at listing some assumptions and limitations within the model, which may lead to further improvements with regard to similar assessments:

- With regard to the time-related coverage of data, which dates back to a maximum of 15 years, the addition of more recent and cross-checked processes and expenditure information could represent a possibility for refinement.
- With respect to the emissions during the operational phase, engine performance is assumed mostly constant, without the inclusion of the operation of the engines at port.
- With regard to the operational phase, the diesel engines' modelling could be improved, as the modelling included herein is quite scaled-down due to time constraints, e.g. machinery maintenance has been disregarded. The above also applies for the modelling of the boilers and propellers.
- The end-of-life phase of the model is an excellent candidate for refinement, given that there is a consistent lack of data throughout. Any addition would increment the reliability of further studies.
- Since silicone-based coatings are a novel technological application, data with regard to the paint's waste management after hull removal or emissions to sea water are scarce and not included. It is pertinent to assess this information in future assessments, in order to avoid the transfer of ecological impacts from one environmental media to another (e.g. reductions in emissions to air, while creating a detrimental waste effluent), during the overall life cycle of the system.

Aside from the proposed eco innovative retrofit and the positive environmental results presented herein, the paper aims to offer practical examples to apply the LCA methodology within the shipyard industry; the methodology can offer the end user the flexibility to environmentally enhance shipyard processes, while improving operation design. Additionally, further practical implementations and real case vessel scenarios with regard to similar eco innovative retrofits can offer international regulatory bodies and lawmakers significant impact data and possibilities for comparison, in order to soundly nominate environmentally efficient fleet emission solutions.

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